Subdaily northern hemisphere ionospheric maps using an extensive network of GPS receivers

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Abstract. Ionospheric total electron content (TEC) data derived from dual-frequency Global Positioning System (GPS) signals from 30 globally distributed network sites are fit to a simple ionospheric shell model, yielding a map of the ionosphere in the northern hemisphere every 12 hours during the January 1-15, 1993 period, as well as values for the satellite and receiver instrumental biases. Root-mean-square (RMS) residuals of 2-3 TEC units are observed over the 20"-80° latitude band. Various systematic errors affecting the TEC estimates are discussed. The capability of using these global maps to produce ionospheric calibrations for silts at which no GPS data are available is also investigated.

introduction

Radio signals propagating through the Earth's ionosphere incur a phase advance and group delay proportional to the integrated electron density along the signal ray path. These effects represent a significant error source for a variety of tracking, navigation, radio science, and radio astronomy applications. The Deep Space Network (DSN) is responsible for navigating spacecraft such as Magellan, Galileo, and Ulysses using single-frequency (S or X band) Doppler and range radio metric data. In order to navigate accurately the radio metric data must be corrected for the dispersive delay effects of charged particles. Ionospheric calibrations are also required for other purposes such as correcting singic-frequency Very 1 .ong Baseline Interferometry (VLBI) measurements and for verifying the calibration of the TOPEX dual-frequency altimeter. In the past the DSN has generated ionospheric calibrations using Faraday rotat ion data or (iual-frequency Global Positioning System (GPS) delay data from a single (on-site) GPS receiver [*Lanyi and Roth*, 1988]. These single-si(c techniques provide only limited sky coverage and are sensitive to data gaps.

in order to improve the accuracy of the ionosphere calibrations, the DSN has begun exploiting an existing world-wide network of GPS receivers to produce global maps of vertical total electron content (TEC). The continuously operating International GPS Geodynamics Service (IGS) network had about 30 stations, as of January 1993, covering a wide range of latitudes from Ny Alesund, Norway to McMurdo, Antarctica [*Melbourne et al.*, 1991]. Assuming a network of 30 ground recei vets and a full GPS constellation, TEC can be simultaneously measured on approximately 240 Iines-of-sight (eight at each ground site). Since the receivers are distributed around the globe, a large fraction of the "ionospheric shell" is sampled in just a few hours. Thus such a network can ultimately provide the capability to make a "snapshot" of the global TEC distribution with a few-hour or belter temporal resolution, and a time series of such maps will reveal the evolution of the global TEC structure. Performing a global fit to data from many silts also allows one to bring much more data to bear on the problem of estimating the satellite instrumental biases. Since the ionospheric delay and the instrumental biases must be estimated simultaneously, wc have found that the tasks of estimating the biases and modeling the ionosphere arc intertwined and complementary. Currently, the uncertainty in the biases is the dominant error source in producing G1'S-based TEC maps. Using multisite fits instead of the older single-si(c technique has led to improved hias values as evidenced by reduced day-to-day scatter i n the bias estimates [scc *Wilson and Mannucci*, 1993].

1 meal maps of TEC over single GPS receiver sites using GPS dual-f ·equency delays have hccn obtained previously by several groups including the authors [*Royden et al.*, 1 984; *Lanyi and Roth*, 1 988; *Coco et al.*, 1991]. The method introduced by Lanyi and Roth assumes that the electron distribution lies in a thin shell at a fixed height above the Earth, and the measured ionospheric delays arc modeled by a two-dimensional polynomial function of shell angular position. in previous papers wc have extended this thin spherical shell fitting technique to multisite GPS data sets using two-dimensional spherical (surface) harmonics as a global hasis. Daily ionospheric maps of the northern hemisphere were produced for 23 clays in January and February of i991 and for 1 i days in October of 1992 [*Wilson et al.*, 1992; *Mannucci c/ al.*, i 992]. These maps were essentiall y a daily average ionosphere, since cacb fit used 24 hours of GPS data. Wc arc currently investigating several ways to improve the time resolution of the maps in order to fully exploit the potential of the global data set [see *Mannucci et al.*, 1993].

In this paper the surface harmonic filling technique has been used for periods as short as 12 hours. Duc to i imited ionospheric shell coverage, the lime span cannel be reduced further with the harmonic fitting technique. The trade-off between time resolution and shell coverage will hc discussed below. A data set consisting of 15 days of GPS data (January i-i 5, 1993) from 30 globally distributed sites in the IGS network has been investigated for this work. A world map showing the station locations appears in Figure 1. Note that only five of the sites are in the southern hemisphere, and (hat the northern hemisphere sites arc confined to a latitude band from 25''-800 except for the lone equatorial site al

Kourou, French Guiana (KOUR). This data set therefore has limited utility for studying the equatorial anomaly. However, the IGS network is growing rapidly (45 sites as of November 1993) and the geographic distribution of sites, particularly in South America and Africa, continues to improve with time.

Ionosphere Model and Estimation Technique

The thin spherical shell model is described in detail by Lanyi and Roth [1988]. Briefly, the vertical TEC is approximated by a spherical shell with infinitesimal thickness at a fixed height of 350 km above the Earth's surface. The TEC is assumed to be time-independent in a reference frame fixed with respect to the Earth-Sun axis for several hours. The intersection of the line-of-sight from the receiver to the satellite with the spherical shell defines a "shell" latitude and longitude, where the zero of shell longitude points toward the Sun and the latitude is defined relative to the Earth's equator. The line-of-sight TEC is assumed to be related to the vertical TEC by an elevation mapping function M(E), which is the simple geometric slant ratio at the shell height h:

$$M(E) = \{1 - [\cos E \;/\; (1 + h/R)]^2\}^{-1/2}$$

where E is the elevation angle and R is the radius of the Earth. Dual-frequency GPS observations provide measurements of line-of-sight TEC, but are corrupted by instrumental delay biases between the L_1 and L_2 signal paths in the satellite transmitter and ground receiver. The instrumental bias can be measured directly for some ground receivers, but the satellite transmitter biases must be estimated or obtained from an independent source. The line-of-sight differential delays for the ith receiver looking at the jth GPS satellite can be modeled by the following expression:

$$\tau^{LOS}_{ij} = \tau^{r}_{i} + \tau^{s}_{j} + K \; M(E_{ij}) \; TEC(\theta_{ij}, \phi_{ij})$$

where τ^{LOS}_{ij} is the line-of-sight differential delay, τ^{r}_{i} is the bias for the ith receiver, τ^{s}_{j} is the bias for the jth satellite transmitter, K (= 0.35) is a constant relating differential delay at L band in nanoseconds (ns) to ionospheric TEC in TEC units (1 TECU = 10^{16} el m^{-2}), $M(E_{ij})$ is the elevation mapping function, and $TEC(\theta_{ij}, \phi_{ij})$ is the vertical TEC at shell latitude θ_{ij} and shell longitude ϕ_{ij}. The vertical TEC over the entire globe can then be fit to a surface harmonic expansion in θ and ϕ, while simultaneously estimating the receiver and satellite biases.

I'here is a trade-off between shell coverage and temporal resolution when producing large-scale TEC maps from GPS data. To achieve adequate shell coverage given a limited number of ground sites and the geometry and angular velocity of the GPS satellites, a certain period of time must pass so that the line-of-sight from the ground silt 10 the satellite can traverse a region of the ionospheric shell. However, the ionosphere is changing during this period 01 lime so the data span should be minimized in order to optimize the accuracy and temporal resolution of the maps. Figure 2 shows the shell coverage for data arcs of 24, t 2, and 6 hours on January 5, 1993. The longitudinal coverage for the 24- and 12-hour data arcs is adequate, but the coverage for the 6-hour data arc is too patchy in longitude to yield a reasonable surface harmonic fit. Note that for the 12-hour data arc, the equatorial coverage spans only half of the longitude range since there is only onc equatorial ground site (as of January 1993).

The ionosphere model used is obviously a simplification. The notion of "mapping to vertical" makes sense only when horizontal TEC gradients arc not 100 large. The assumption that the ionospheric shell height is constant everywhere is also an approximation. Simulations with Chapman profiles show that the functional form for the thin-shell mapping functions actuall y approximates the mapping function for distributed profiles as long as the height is chosen correctly (G. Hajj, private communication, 1993). But choosing the incorrect height can lead to a biased estimation of vertical TEC along a satellite track.

Another limitation of this approach is the problematic assumption that the ionosphere is independent of time over several hours in the Sun-fixed reference frame. The ionosphere at a fixed shell location will vary in time as a result of variations in the solar flux and other dynamics, such as traveling ionospheric disturbances. More importantly, a line of constant geomagnetic latitude varies in time by ±1 10 over 24 hours as expressed in the Sun-fixed longitude and geographic t atitude coordinate system, duc to the offset between the magnetic and rotational poles of the Earth. Thus the longer the span of data in a fit, the more onc is averaging over magnetic-ally in fluenced variations in the. ionosphere.

The accuracy **Or** the ionospheric TEC maps obtained from GPS data is strongly affected by uncertainties in the satellite and receiver biases. These can be estimated independently along with the ionosphere since they do not share the same elevation angle dependence as the TEC. Because the elevation mapping function is only approximate and the ionosphere at a fixed shell location is changing during the time span of the fit, the ionosphere may be systematical I y mismodeled, leading to an improper separation of the elevation-dependent TEC from the elevation-independent biases. As a result, the bias estimates obtained from any one fit may be corrupted by ionospheric mismodeling. However, the biases are constant on a timescale of weeks to months, so better bias values can be obtained by averaging the estimates from many fits over 10-15 days.

To further reduce the effects of ionospheric mismodeling, the estimation procedure can be applied using only nighttime data, when the ionosphere is smaller and less variable, and therefore less susceptible to modeling errors. Nighttime data are defined to be those observations with ecliptic shell longitudes in the nighttime quadrant opposite the Sun. Unfortunately, this strategy is also problematic since at nighttime, when the F_2 layer (the part approximated by the shell) is low, the protonosphere can contribute as much as 50% of the total TEC [*Davies*, 1980]. The best strategy for estimating the biases might be to use nighttime data from only high-latitude sites where there is no protonosphere contribution, but then one has to worry about the aurora. (In more recent work we have abandoned the problematic nighttime strategy since we observed that the nighttime and daytime global fits yielded very similar biases anyway.)

The following estimation strategy was used to produce the global maps presented in this paper. Each multisite data arc is fit in a two-step process: first, the nighttime data alone are fit to determine receiver and satellite biases, and then, fixing the biases at average values obtained from nighttime fits performed over 10-15 days, the full daytime and nighttime data set is used to estimate the global ionosphere. in both steps the vertical TEC is modeled by 8th-order surface harmonics. Only TEC observations with elevation angles above 10" have been used in the fits. For a 2-minute data rate from 30 receivers, a full 12-hour fit consists of approximately 60,000 observations. Since the observable is sensitive only to the sum of the receiver and satellite biases, several of the receiver biases are constrained tightly (a priori standard deviation of 1 ns or 3 TECU) to values based on periodic receiver calibrations, while the rest of the receiver biases and all of the satellite biases are essentially unconstrained. This strategy allows one to determine absolute levels for lilt satellite and receiver biases, and it reduces sensitivity to a single erroneous receiver calibration.

Results

Multisite fits of the GPS data from 30 IGS sites were performed for the January 1-15, 1993 period. Since the majority of the sites are in the northern hemisphere, results are presented only for a limited latitude band of

20° to 80° N. A contour map of vertical TEC obtained from a 24-hour fit on January 4, 1993 is shown in Figure 3. The TEC is expressed in the usual TEC units where 1 TECU = 10^{16} el m^{-2}. Note the peak in the ionosphere just east of 0° longitude (the Sun axis) and the characteristic fall-off at nighttime. Figure 4 shows contour maps of three 12-hour fits covering the period of 0000 UT on January *4* to 1200 UT on January 5. These maps are representative of the 30 12-hour maps produced for the 15- day period. The temporal evolution of ionospheric TEC can be investigated by examining a time series of global TEC maps. Using a false-color representation of TEC, a color ionosphere movie has been produced from the sequence of 30 12-hour maps. The progressive change in the ionospheric structure over days to weeks is quite evident in the color movie.

To determine the accuracy of the harmonic fits, a map has also been made of the vertical residual ionosphere (observed TEC mapped to vertical minus the fit). Figure 5a shows a gray-scale map of the vertical root-mean-square (RMS) residuals for the 24-hour fit shown in Figure 3. The map is formed by accumulating the RMS of the residuals into a 1°-by-1° grid in latitude and longitude. White boxes represent grid squares for which there are no data as a satellite track never passed through that square. The residuals range from 0 to 20 TECU but most are in the range of 0 (light gray) to 10 (black) TECU. The total RMS of the residuals is 4.3 TECU. Note that the residuals are below 5 TECU nearly everywhere in the 20°–80° latitude band. Only in a localized region near 20° latitude, where the coverage is sparse, do the residuals rise above 10 TECU. The vertical RMS residuals for the 12-hour map in Figure *4a* are shown in Figure 5b. The total RMS of these residuals is 2.1 TECU. Note that the residuals for the 12-hour map are smaller than those for the 24-hour map, as expected, since for the 12-hour fits there is less time-averaging than for the 24-hour fits. For the 24-hour fit there can be two observations at the same shell position separated by nearly *24* hours. If the ionosphere has changed substantially, the two observations will not be consistent and the fit cannot match both of them, resulting in a large residual. This effect may also account for the large residuals in the lower latitude region of the map, since in this region variations due to the magnetic pole rotation are expected to be largest.

Another way to check the robustness of the estimation strategy is to remove one or more sites from the data set, perform a fit with the remaining sites, and then calculate the vertical residuals for the observations at the removed sites. The result is a measure of how well the maps predict the TEC at shell locations where there are no data. Figure 6 shows a plot of the Usuda, Japan (USUD) vertical residuals versus shell longitude for a 24-hour fit on January 5, excluding the Usuda data. Except for a few GPS tracks near the Sun axis, the residuals are below 5 TECU in magnitude. The residuals are essentially unchanged when the data from Usuda are added to the fit. The RMS of the residuals without Usuda data is 2.8 TECU; with Usuda data it is 2.6 TECU. This striking result illustrates both the benefits and problematic aspects of 12- or 24-hour surface harmonic fits. Using a long span of data and fitting the data on a Sun-fixed shell effectively spreads the longitudinal coverage, so the TEC above Usuda can be estimated by using data from sites which cover Usuda's latitude band but are remote in longitude. Thus, using harmonic fits to produce global maps gives one the capability to predict the vertical TEC at a site with no GPS receiver (or no data that day) by using GPS data from remote sites. However, near the Sun axis where the ionosphere is large and can exhibit large temporal fluctuations, the temporal averaging inherent in the fits may lead to large errors. We anticipate that the harmonic fitting strategy will be more effective in the midlatitudes where the ionosphere is better behaved (fewer large temporal fluctuations) than in the equatorial and auroral regions.

To investigate the accuracy of the remote calibration capability, one can look at the vertical TEC above a site during a 24-hour period, as predicted by a global map which does not include GPS data from that site. This prediction can then be compared to estimates obtained from single-site and global fits that do use the data from that site. Figure 7a plots the vertical TEC directly above the Goldstone (GOLD in Figure 1) receiver site versus time for the 24 hours of January 5 as predicted by five different fits: (1) a single-site fit of Goldstone data, (2) a 24-hour global fit including the Goldstone data, (3) a 24-hour global fit excluding the Goldstone data, (4) a pair of 12-hour global fits including the Goldstone data, and (5) a pair of 12-hour global fits excluding the Goldstone data. The five predictions agree to within a few TEC units. Figure 7b shows a similar plot of the five predictions for the TEC above the Usuda site. The Usuda site is more isolated than the Goldstone site, but for the 24-hour global fits the agreement with the single-site fit is still quite good, since Usuda's latitude band is well covered by other sites.

The effect of choosing an incorrect elevation mapping function has been investigated by performing the estimation procedure with a different elevation angle cutoff. Two 24-hour maps were made using 10° and 20° elevation angle cutoffs. The difference map shown in Figure 8 was formed by differencing two 1°-by-1° grids. The difference grid points have a mean of -0.14 TECU and a standard deviation of 0.85 TECU. The map has been restricted in latitude range to 30”-80° since the larger elevation cutoff reduces the coverage in the latitude range of 20°–30°. Note that the difference varies smoothly between positive and negative values. This could correspond to a smoothly varying crrm in shell height over the given regions. For both maps a constant shell height of 350 km is assumed. If the "effective" shell height is larger (smaller) than 350 km, then mapping errors at low elevation will cause the ionosphere to be underestimated (overestimated).

Conclusions

A world-wide network of GPS receivers provides a unique opportunity 10 continuously monitor the ionosphere on a global scale. While the IGS network had severely 1 imited equatorial and southern hemisphere coverage as of 1992, approximately 15 receiver sites were added in 1993 and more will come on-line in the near future. Larger, more uniformly distributed networks will provide denser longitudinal coverage for shorter data arcs, enabling ionospheric mapping with hourly or subhourly temporal resolutions. Since the IGS network is permanent and continuously operating, hourly global ionospheric maps could be produced continuously,

Wc have produced global TEC maps every 12 hours for 15 days in January 1993 by fitting vertical TEC measurements from 30 GPS receiver sites to a two-dimensional spherical harmonics basis. Since the majority of the receiver sites arc in the northern hemisphere for this data set, the maps arc only useful for the latitude band of 20”-80” in the northern hemisphere. The RMS of the fit residuals is Icss than 3 TECU for that latitude band. By fitting the data on a Sun-fixed she] i, wc have. developed a rough capability to predict the ionosphere at an isolated site using GPS data from other sites in the same latitude band. Preliminary results indicate that, for sites in the midlatitudes, tile global maps arc able to predict the diurnal curve of vertical TEC over a site to within 5 TECU. Further study and comparisons to independent ionosphere measurements will be required 10 verify the accuracy of the global maps.

The surface harmonic fitting technique used in this analysis limits the maps to a time resolution of 12 hours or longer. Efforts arc under way to improve the time resolution by using a better set of basis functions. A disadvantage of surface harmonics is that they arc nonzero over the entire sphere; [hey have “global supper l.” For investigating ionospheric behavior on timescales much shorter than 12 hours, it will be necessary to usc basis functions with “local support,” that is, basis functions which arc nonzero only over a limited urea of the shell. We are developing a triangular interpolation technique in which the ionospheric shell is tiled with triangles and the TEC at each vertex is estimated by local interpolation of the TEC data within the triangles. The TEC at each vertex is treated as a stochastic parameter (random walk) and is updated every hour [*Mannucci et al.*, 1993]. Using the local triangular basis with a stochastic estimation strategy should produce more accurate maps when coverage is sparse.

As we gain more experience with mapping techniques, we anticipate that a more physical parameterization of the ionosphere will be required to accurately model the high-latitude anti equatorial ionospheres. The physics of the three ionospheric regions (equatorial, midlatitude, and auroral) is quite distinct. In regions where data coverage is sparse, a priori information from a semi-empirical ionosphere model which incorporates the relevant ionospheric physics (e.g., the Bent [*Bent* e/ al., 1976] or PRISM models [*Anderson*, 1993]) could be used to bridge the gaps in the data.

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Figure 1. This map shows the GPS receiver locations for the International GPS Geodynamics Service (IGS). Receivers at the locations denoted by a solid circle provided the data used in this paper. Additional locations that became available as of March 1, 1993, are denoted by a cross.

Figure 2. Ionospheric shell coverage plots for the receiver network of Figure 1 (solid circles only) for three time intervals on January 5, 1993. A point is plotted at the shell intercept point for each link between a receiver and satellite transmitter. A Sun-fixed coordinate system is used for these plots: 0° longitude is the Sun-Earth direction, and the Earth rotates underneath. The latitude of this system is the same as geographic. (a) Coverage for the period 0000-2400 UT; (b) coverage for 0000-1200 UT; and (c) coverage for 0600-1200 UT. Since there is only a single receiver in the equatorial region at Kourou, French Guiana, the equatorial coverage is quite sparse for the 6- and 12-hour periods.

Figure 3. Global ionospheric TEC distribution for January 4, 1993, derived from a 24-hour fit. Contours are labeled in units of TEC (equal to 10^{16} el m^{-2}). Zero degrees Sun-fixed longitude corresponds to local noon. As expected, the ionosphere peaks in the low latitudes on the dayside around 30° Sun-fixed longitude (1400 LT), falls off with increasing latitude, and reaches a minimum on the nightside.

Figure 4. Global ionospheric TEC distribution for January 4-5, 1993, derived from three 12-hour fits. Contours are labeled in units of TEC (equal to 10^{16} el m^{-2}). (a) Fit of data from 0000-1200 UT on January 4; (b) fit of data from 1200-2400 UT on January 4; and (c) fit of data from 0000-1200 UT on January 5.

Figure 5. Gray-scale map of fit residuals on January 4, 1993. RMS residuals were accumulated into a 1°-by-1° grid. White boxes are regions without coverage. The range is from 0 (light gray) to 10 TECU (black). (a) Residuals for a 24-hour fit (total RMS = 4.3 TECU). (b) Residuals for a 12-hour fit using data from 0000-1200 UT (total RMS = 2.1 TECU).

Figure 6. Vertical residuals (observed mapped to vertical minus the fit) for the Usuda site on 93/01/05. The fit is a 24-hour fit excluding the Usuda data. The largest residuals occur daring the daytime (near 0° in Sun-fixed longitude).

Figure 7. Vertical TEC directly above (a) Goldstone and (b) Usuda during the 24 hours of January 5 as predicted by five different fits. The solid line is the single-site fit and the other lines are global fits. Notice that the global fits excluding data from the chosen site are within a few TEC units of the single-site fit.

Figure 8. The difference of two 24-hour TEC maps which differ in elevation angle cutoff: 20° versus 10°. The difference map is formed by differencing two 1°-by-1° grids. Notice that the differences are small (1-2 TECU) and nearly zero mean, which indicates that including data down 10 10° dots not significantly alter the maps.

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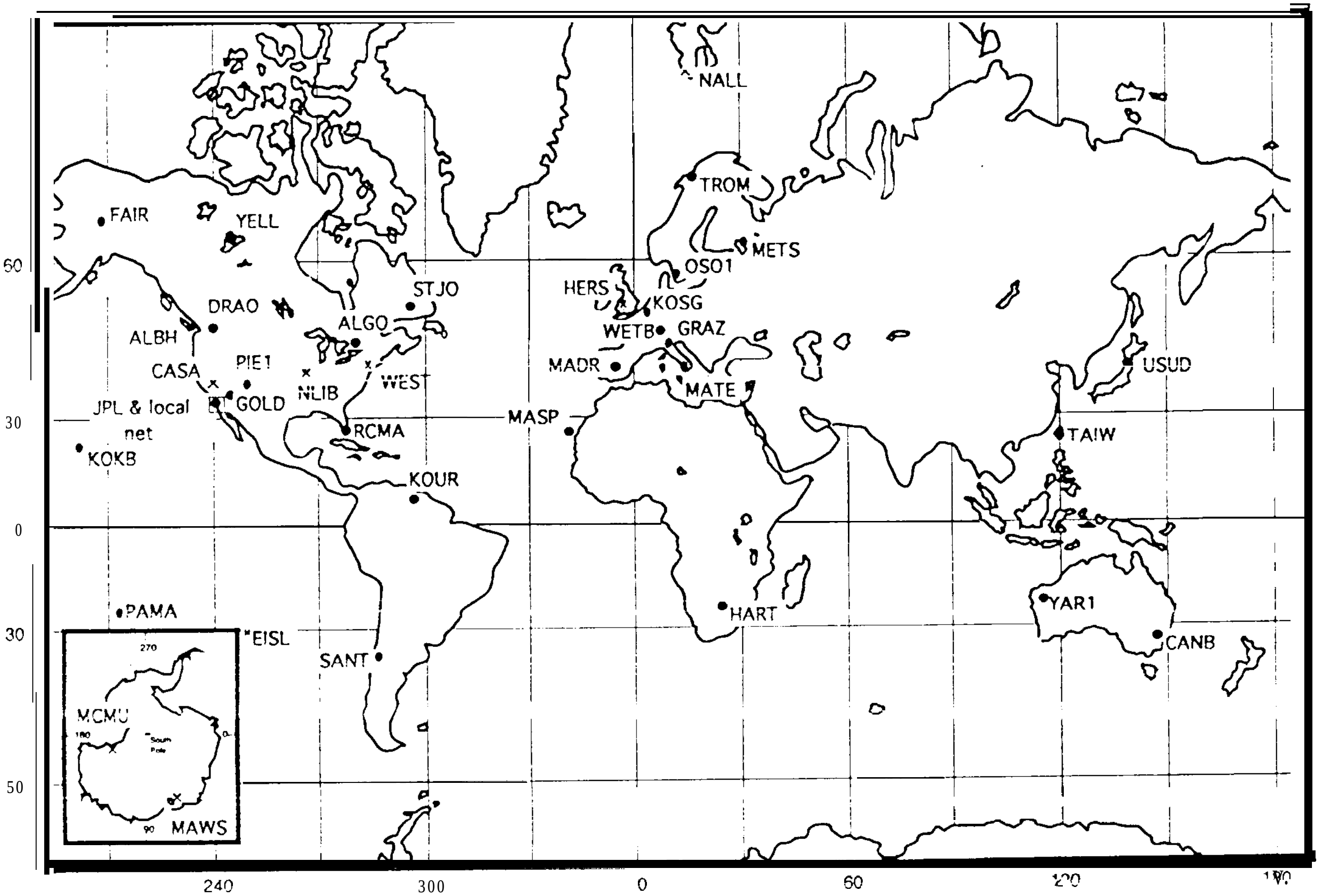


IGS GPS Receiver Network

. Rogue Receiver Network For January 1993

x Currently Operating Receivers as of March 1 1993

Figure 1 — This map shows the receiver locations for the International GPS Service. The receivers at the locations denoted by a filled circle Provided the data used in this paper. Additional locations that became available as of March 1, **1993** are denoted by an X-mark.

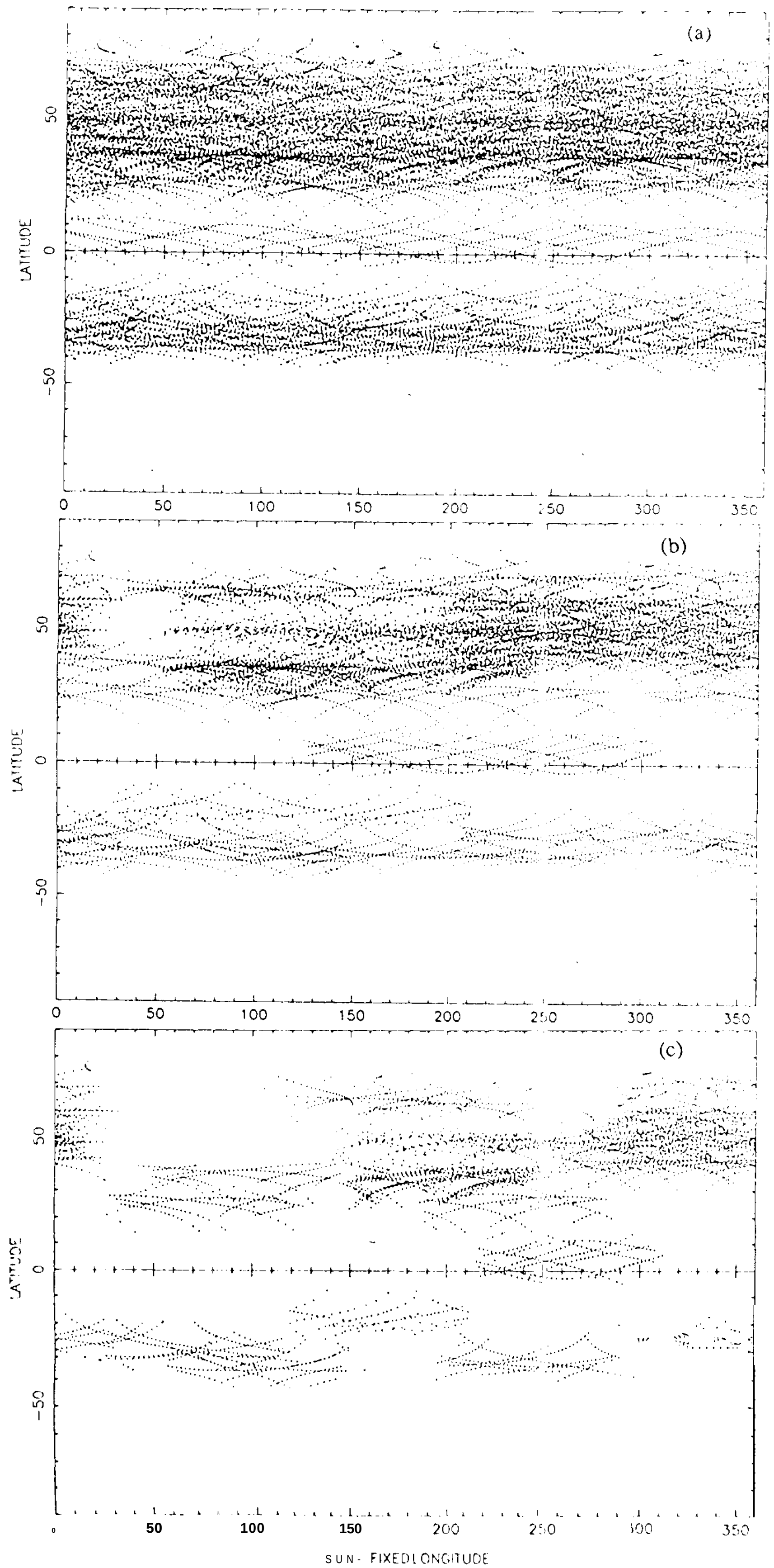
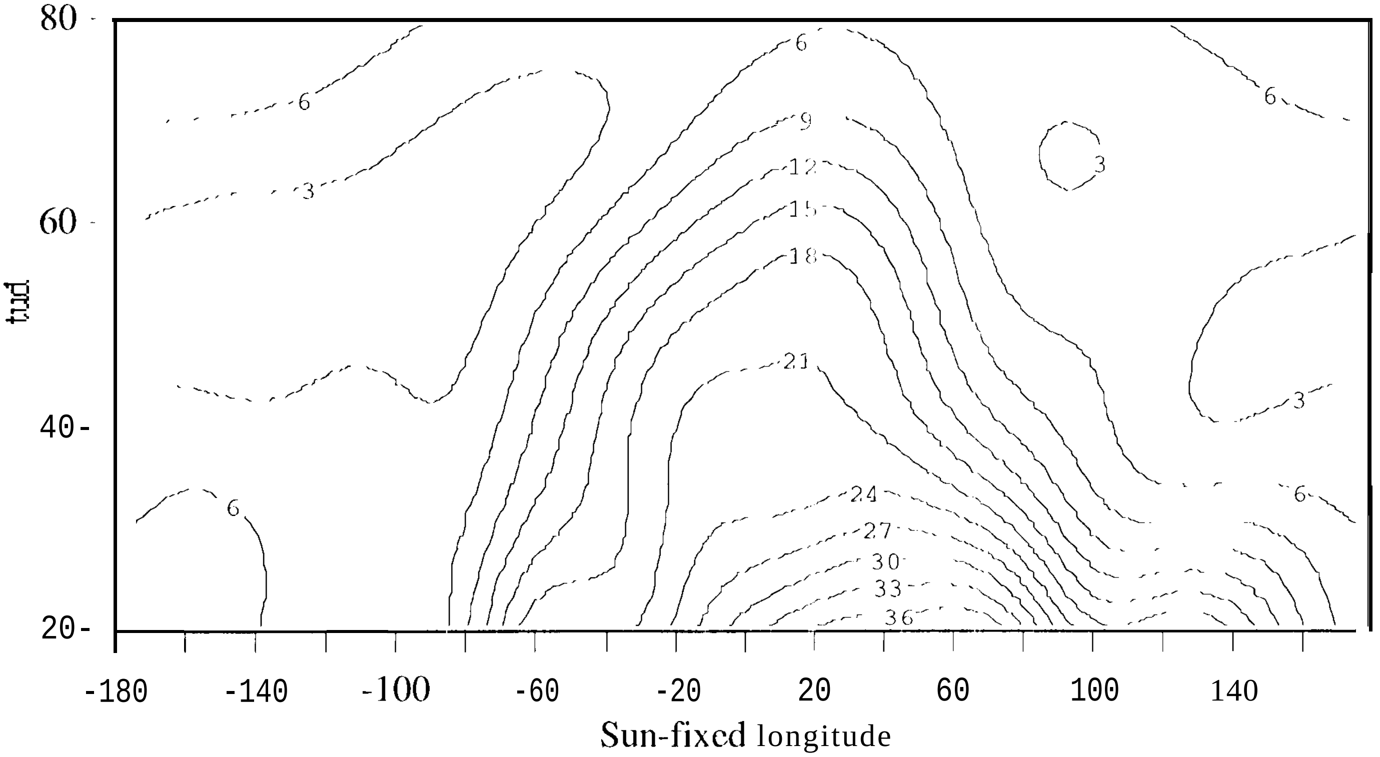


Fig 2

~~**Figure 3.** Fig. 3~~ *shows "coverage plots" for the reciever network of Fig. 1 (filled circles only) for three time intervals on January 5, 1993. A point is plotted for each shell intercept point made between a receiver and transmitter. The standard "sun-fixed" co-ordinate system is used for these plots: 0 degrees longitude is the Sun-Earth direction and the Earth rotates underneath. The latitude of this system is the same as geographic. Fig. 3a which covers the period 00:00-24:00 UT on January 5. A single receiver in the equatorial region (Kourou, French Guyana) provides sparse coverage there. In Fig. 3b, the shell coverage for the period 00:00-12:00 UT is shown. In Fig. 3c the coverage for the 6-hour period of 06:00-12:00 UT is shown.*



80
60
40
20
tud
6
3
6
6
9
12
15
18
21
24
27
30
33
36
3
6
3
6
-180
-140
-100
-60
-20
20
60
100
140
Sun-fixed longitude

Figure 3.

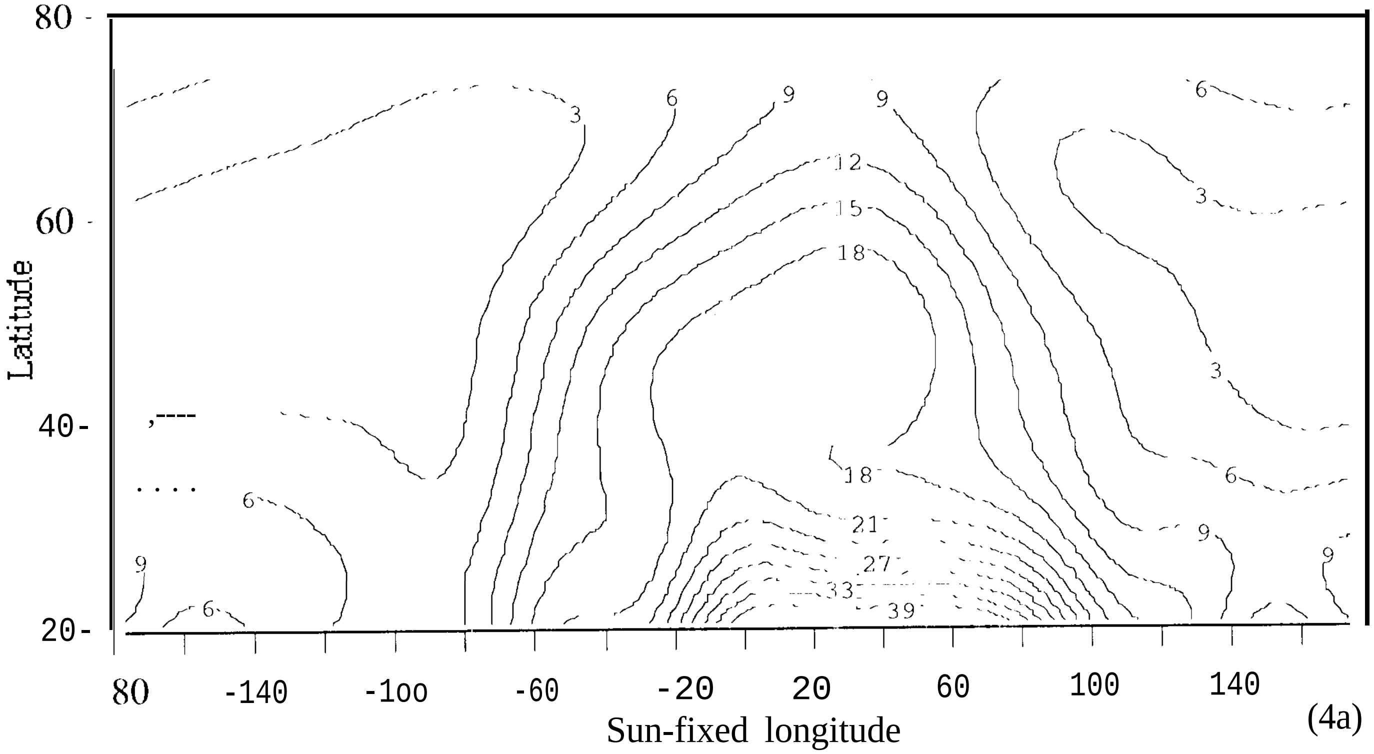

80
60
40
20
Latitude
80
-140
-100
-60
-20
20
60
100
140
Sun-fixed longitude
(4a)
3
6
9
12
15
18
21
27
33
39

Figure 4a.

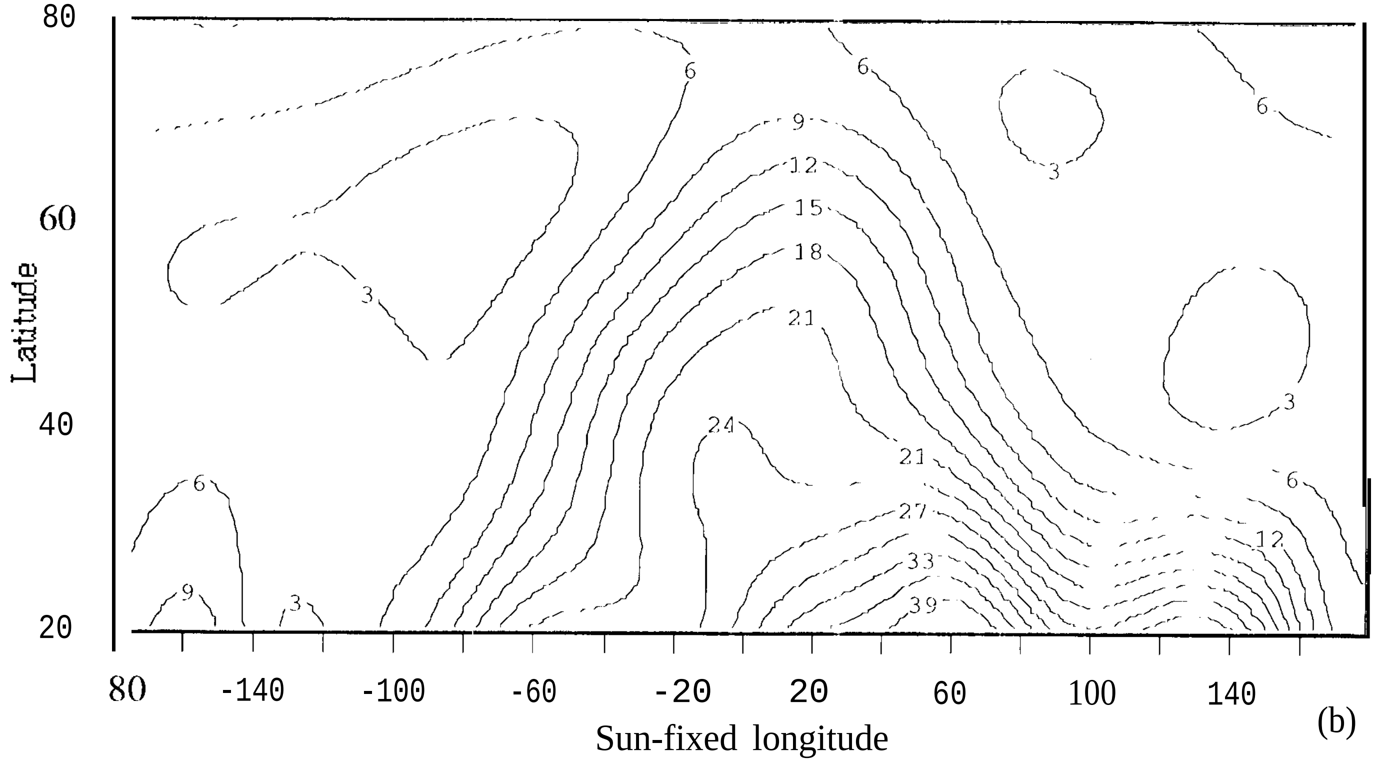
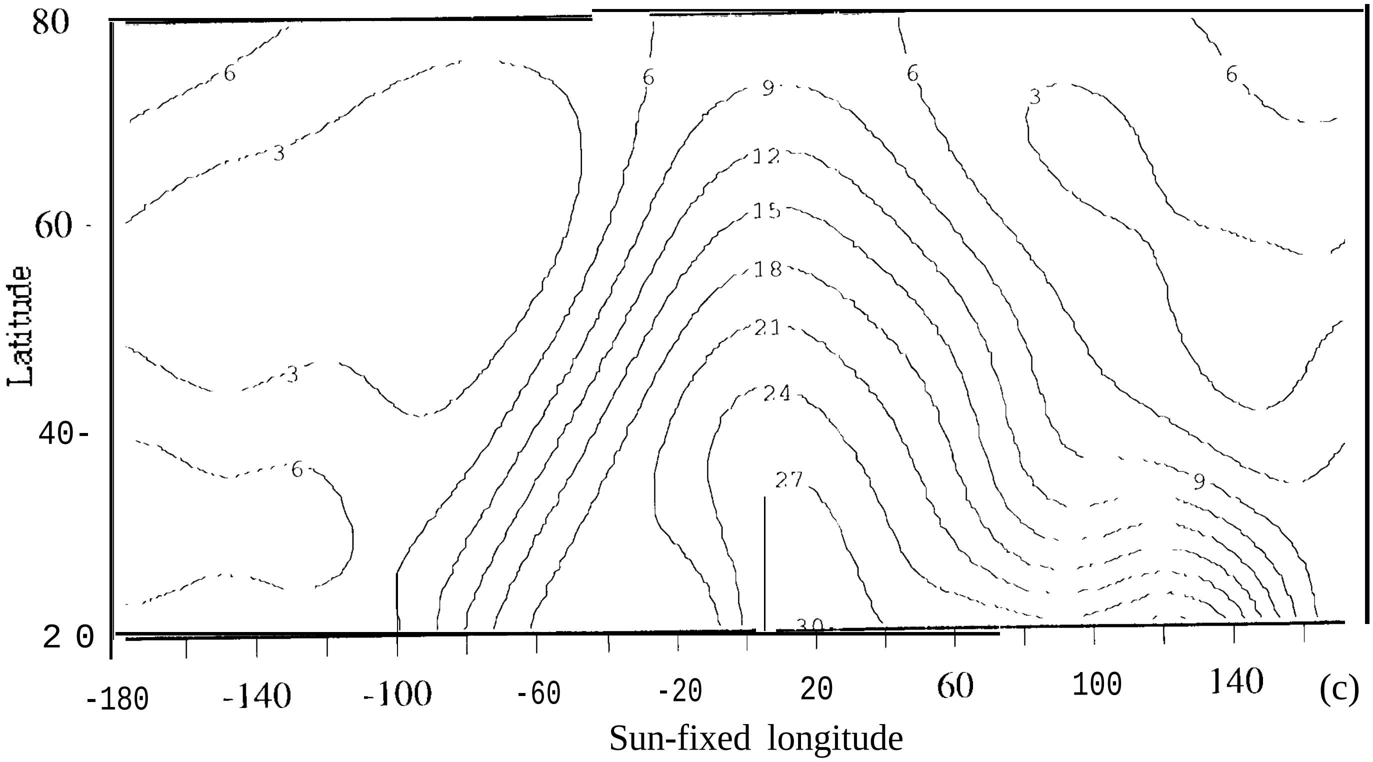

80
60
40
20
Latitude
80
-140
-100
-60
-20
20
60
100
140
Sun-fixed longitude
(b)
6
6
6
9
12
15
18
21
24
21
27
33
39
3
3
3
6
9
3
6
12

Figure 4b.



80
60
40
20
Latitude
-180
-140
-100
-60
-20
20
60
100
140
(c)
Sun-fixed longitude
3
6
9
12
15
18
21
24
27
30

Figure 4c.

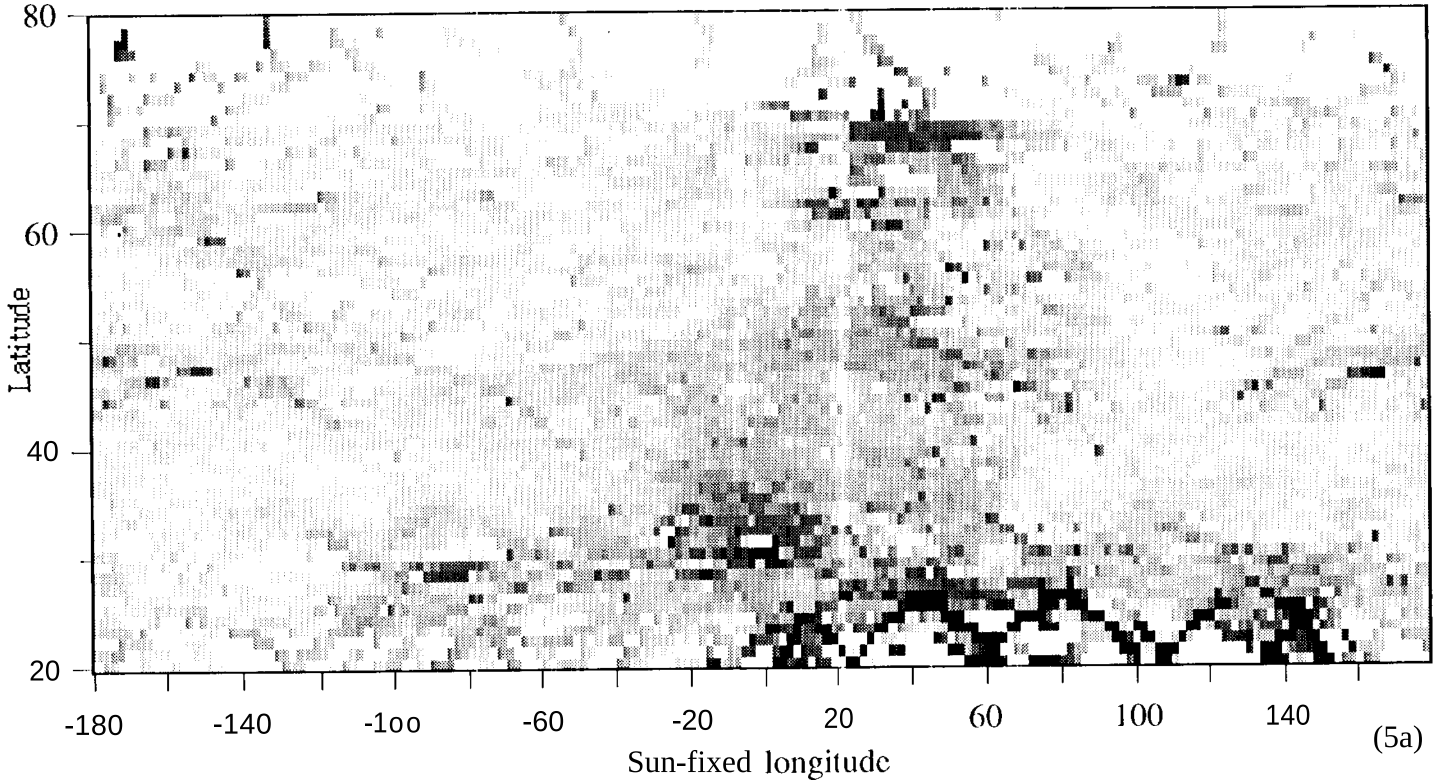
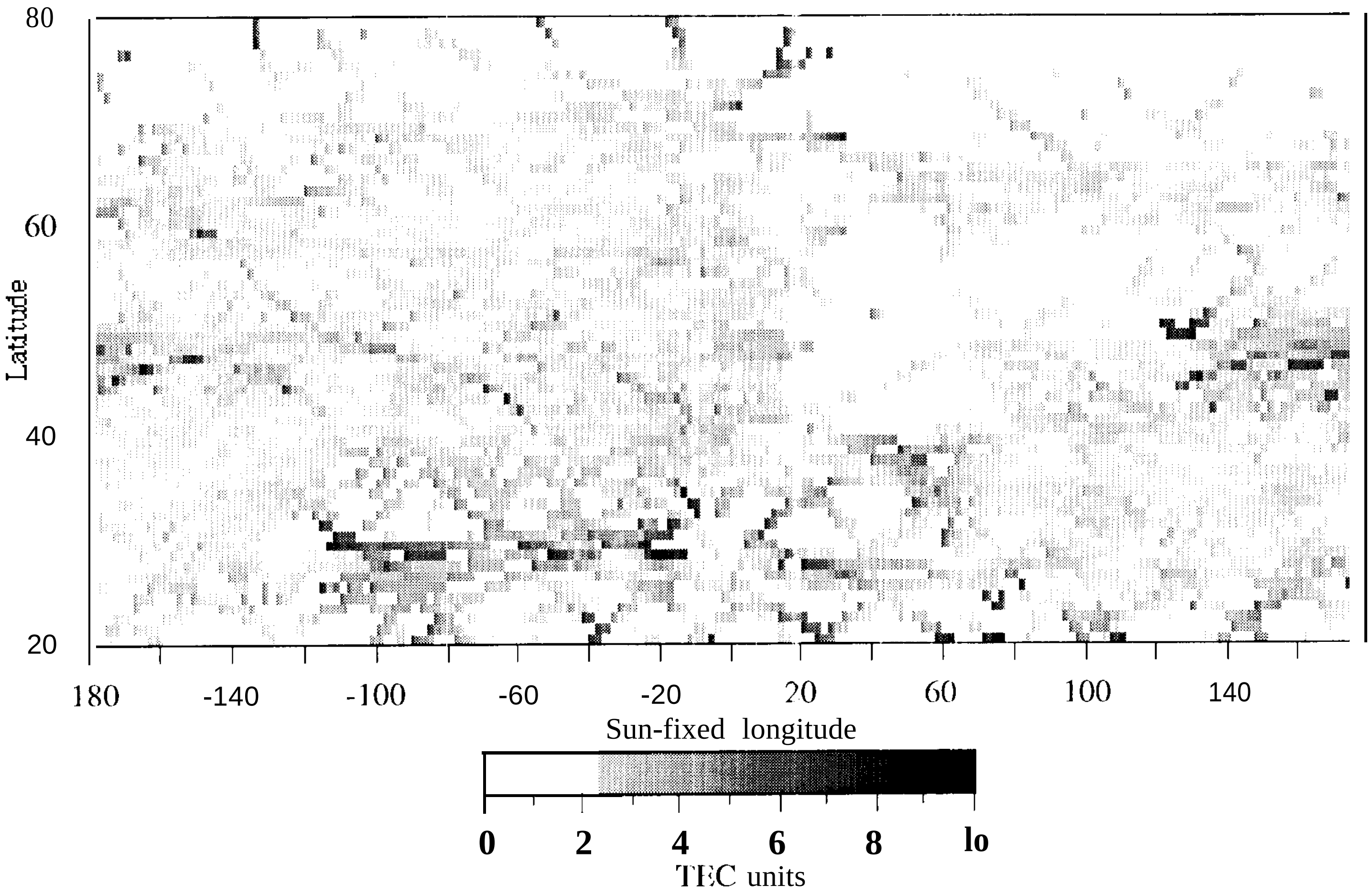
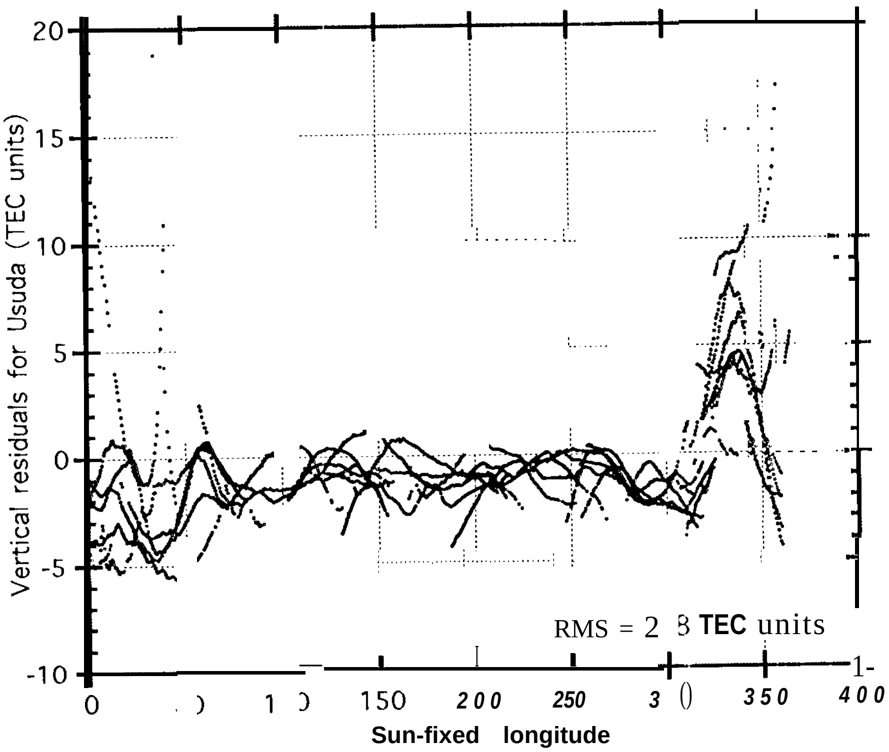

80
60
40
20
Latitude
-180
-140
-1oo
-60
-20
20
60
100
140
(5a)
Sun-fixed longitude

Figure 5a.



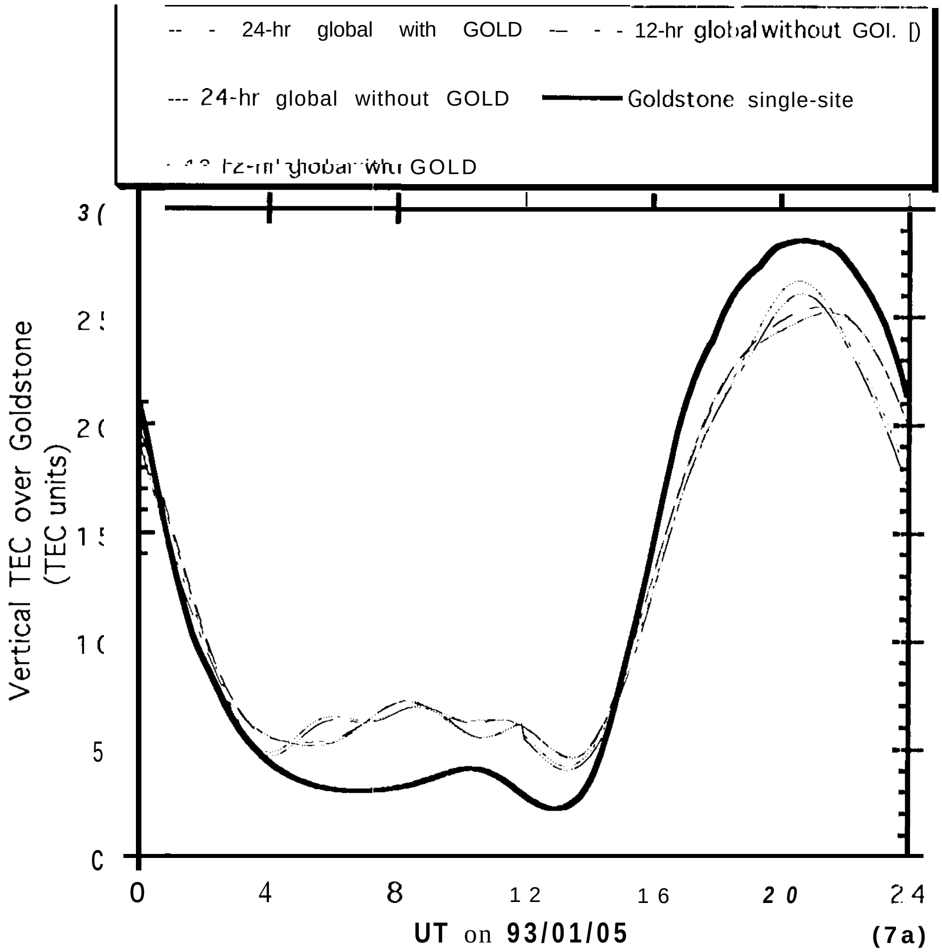
80
60
40
20
Latitude
180
-140
-100
-60
-20
20
60
100
140
Sun-fixed longitude
0
2
4
6
8
lo
TEC units

Figure 5b.



Vertical residuals for Usuda (TEC units)
RMS = 2 3 TEC units
Sun-fixed longitude

Figure 6.



24-hr global with GOLD
12-hr global without GOLD
24-hr global without GOLD
Goldstone single-site
12-hr global with GOLD
Vertical TEC over Goldstone (TEC units)
UT on 93/01/05
(7a)

Figure 7a.

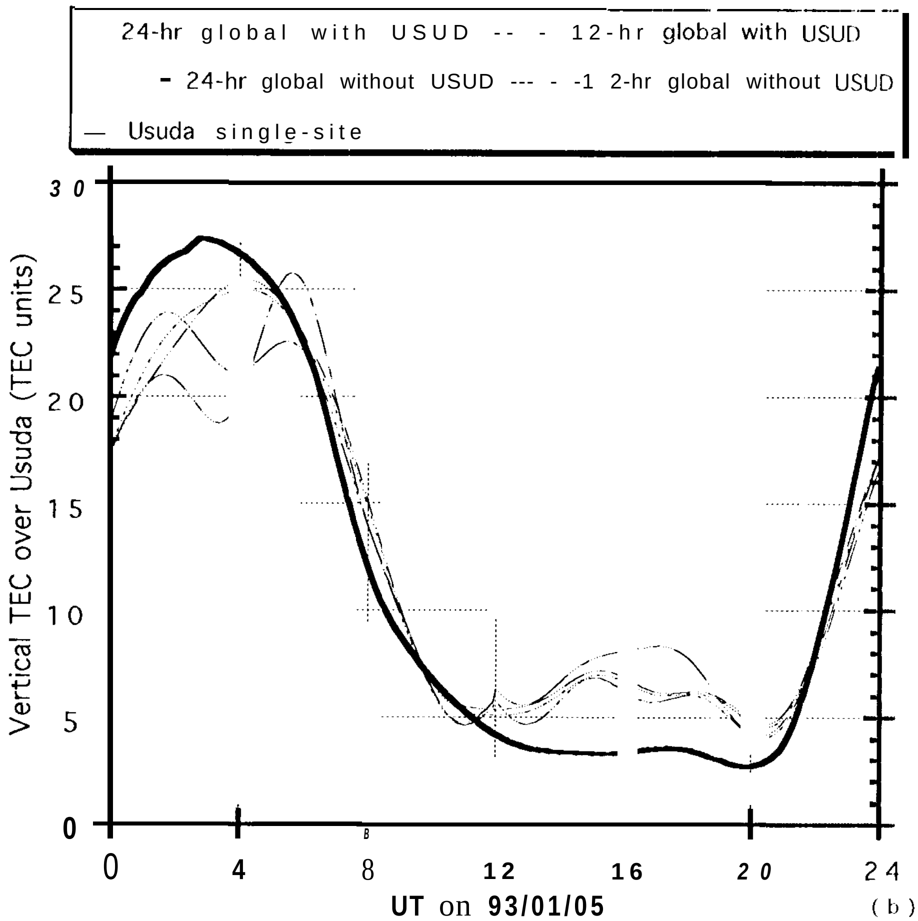

24-hr global with USUD -- - 12-hr global with USUD
- 24-hr global without USUD --- - -1 2-hr global without USUD
— Usuda single-site
Vertical TEC over Usuda (TEC units)
30
25
20
15
10
5
0
0
4
8
12
16
20
24
UT on 93/01/05
(b)

Figure 7b.

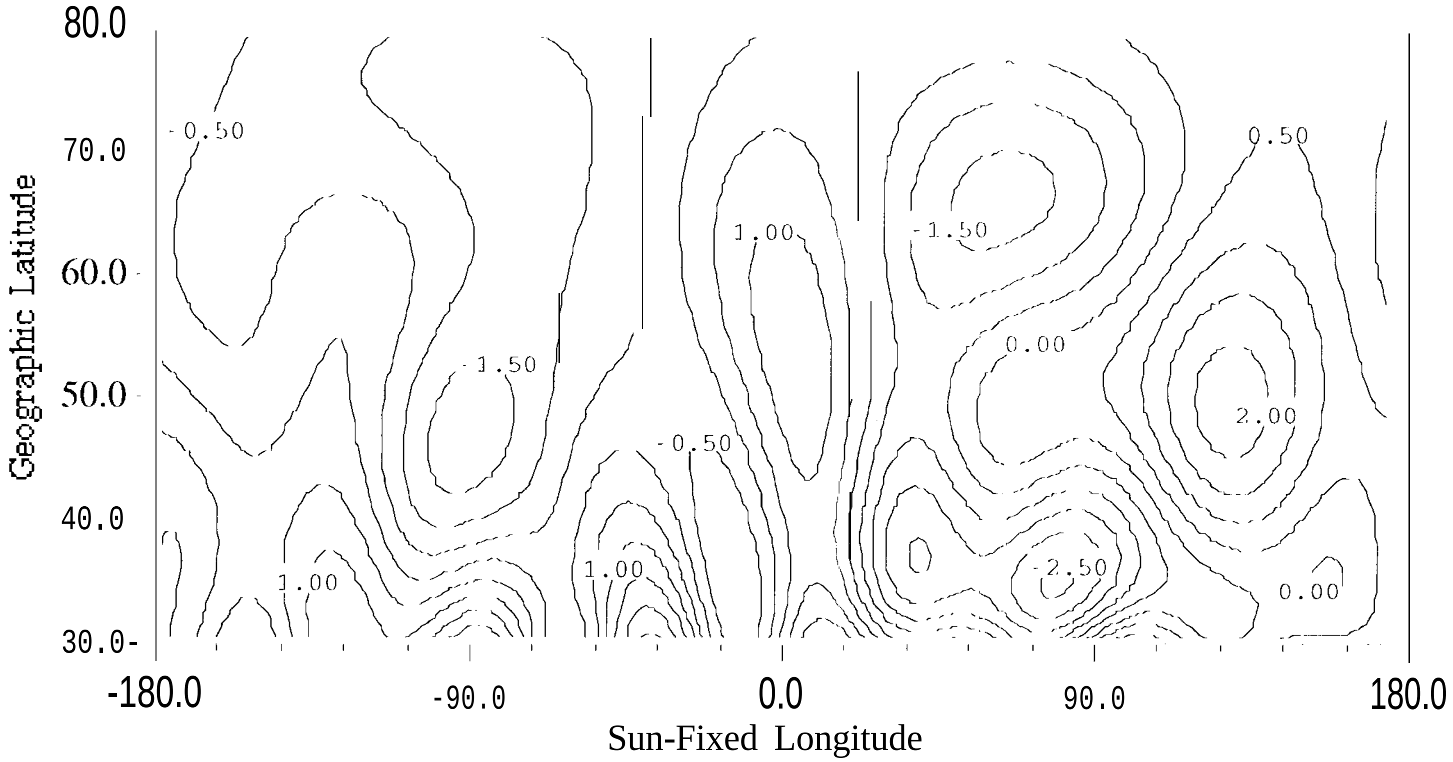

80.0
70.0
60.0
50.0
40.0
30.0
Geographic Latitude
-180.0
-90.0
0.0
90.0
180.0
Sun-Fixed Longitude
-0.50
1.00
-1.50
0.00
2.00
-2.50
0.50

Figure 8.